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WEAR AND CORROSION BEHAVIOUR OF FRICTION STIR WELDED ALUMINIUM ALLOYS- AN OVERVIEW

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ABSTRACT

The need to enhance the integrity and durability of welds to minimize cost and material wastage has led to the demand for more understanding of weld degradation processes, such as wear due to mechanical loading and corrosion when the materials are operated under corrosive conditions. Corrosion and wear in friction stir welding of some aluminum alloys have been investigated separately, understanding how friction stir welds perform under wear and corrosion conditions are significant, so that the durability and lifetime of welds can be predicted and extended. This paper reviewed available literature concerning the development in tribological and corrosion behavior of friction stir welds of both similar and dissimilar aluminum alloys. The review also highlighted various forms of wear and corrosion and factors affecting their mechanism in friction stir welds of aluminum alloys. The review generally showed that corrosion and wear are significantly influenced by the processing parameters employed for the welding and the resulting microstructure and mechanical properties of the welds. The need for further studies on the synergistic or antagonistic effects of the combination of wear and corrosion on friction stir welding of aluminum alloys is also highlighted.

KEYWORDS: Aluminum Alloys, Corrosion, Friction Stir Welding & Wear

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Original Article

INTRODUCTION

Aluminum alloys are principal materials that have found usage in many industries as a result of its mechanical properties, structural virtues, fabrication, high resistance to corrosion, weldability. etc. (Elatharasan &Kumar, 2014; Vieira, Rocha, Papageorgiou, & Mischler, 2012). Among the various welding methods used to join metals together, especially low-temperature alloys like Aluminium, friction stir welding has emerged the most suitable today for processing Aluminium alloys. This is attributed to its numerous merits over conventional fusion welding techniques. Friction stir welding technology is a joining technique that made use of a tool rotating with a shoulder and pin deepened into the joint of the two materials to be welded and then traverse along the line to form the weld. Heat is produced by the frictional movements of the rotating tool on the joint workpiece. This heating result in plastic deformation of the material at high temperature. This welding technology has found applications in many industries and has been utilized to join Aluminium alloys both homogenous and heterogeneous alloys.(Givi & Asadi, 2014), (Hovanski, Carsley, Clarke, & Krajewski, 2015), (Padhy, Wu, & Gao, 2017),

During Friction stir welding of Aluminium and its alloys, the plasticization that occurs changes the welded joint microstructure and mechanical properties. These changes affect the mechanical and electrochemical

behavior of welds in terms of wear and corrosion.(Threadgill, Leonard, Shercliff, & Withers, 2009) The durability and lifetime of welds in mechanical devices critically depend on their corrosion and wear resistance (Esther T Akinlabi, Andrews Anthony, Stephen A, Akinlabi 2014). Corrosion and wear have been identified as a key factor responsible for material degradation. Many researchers have been attracted to the friction stir welding technology and of recent particular attention are being given to the wear and corrosion behavior aspects of the welded joints.

This review is aimed at presenting an overview of reported findings on wear and corrosion behavior of friction stir welding of Aluminium and its alloys, and the need for further research in the field.

CORROSION IN FRICTION STIR WELDING OF ALUMINIUM ALLOYS

Corrosion can be explained as the decay of metal following a chemical reaction with its immediate environments. (Givi & Asadi, 2014), (Ponthiaux, Wenger, & Pierre, 2012). Corrosion occurs in metals mainly through electrochemical means between the surface of the metal and the electrolyte. Corrosion in metals can occur in different forms. (Ponthiaux et al., 2012), (Kuiry, 2012), (Arora, Mukherjee, Grewal, Singh, & Dhindaw, 2014), Figure 1 shows different categories and forms of corrosion. A brief description of these forms of corrosion in metals is highlighted below.

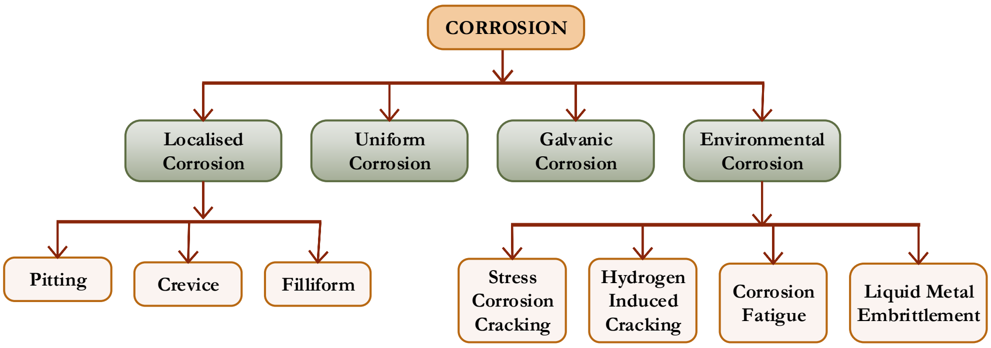

Figure 1: Schematic representation of corrosion and its different forms

- **General Attack/Uniform Corrosion**: This occurs when the entire surface of the metal structure is affected. This type of corrosion is easily predictable and therefore can be easily prevented.
- **Localized Corrosion**: This happens when only a portion of the metal surface is affected. Localized corrosion can be in the following forms.
- **Pitting Corrosion**: Created small holes in the metal surface. It happens in a localized area of the metal due to a broken layer of the protective oxide.
- **Crevice Corrosion**: This occurs when liquid stagnated in a crevice over a long period of time and reduction in Oxygen or acidic conditions of the environment. Examples include clamps, welded joints, and threaded portions
- **Filiform Corrosion**: This occurs when water gets under coatings e.g. paints, weakness.
- **Galvanic Corrosion**: This takes place when two metals having varying electrochemical potentials are found in an electrolyte such as salt water, the metals with greater potential is called anode and the other with lower potential acts as a cathode. An electrochemical reaction takes place between the metals causing the anode to dissolve or corrosion to occur. Galvanic corrosion occurrence depends on these three factors. These are; the presence of dissimilar electrochemical metals, electrical contacts of the metals and the presence of the metals in an electrolyte.

- **Environmental Cracking**: Stress from the environment, temperature and chemicals can make some metals to crack or fatigue or become brittle. This type of corrosion include:
- Stress corrosion cracking (SCC)
- Corrosion fatigue
- Hydrogen-induced cracking
- Liquid metal embrittlement.

Measurement of Corrosion

An Electrochemical measuring device is used to analyze results obtained from the corrosion test system. It performs open circuit potential measurements, electrochemical polarization, electrochemical impedance, yield corrosion potentials, current data and rate of materials removal own to corrosion. (Kuiry, 2012), (Ponthiaux et al., 2012).

The region of weldments that are prone to corrosion in most alloys is generally predictable. An example, very known to professionals is Austenitic stainless steel, where decay in welds occur own to chromium removal by the formation of chromium carbides in the heat affected zone (HAZ). (Donatus, 2017). For Aluminium alloys, it is not easy to predict the corrosion morphology of the weldments. Factors like thermomechanical treatments grain sizes, the composition of alloys, types of precipitates, characteristics of the near surface deformed layers and processing parameters influence the corrosion susceptibilities of the weldments (Donatus, 2017). Available works on the extent to which, these factors above influence corrosion is reviewed below.

Effects of Microstructure on Corrosion

Aluminium alloys consist of about eight series. The alloy in each series constitutes different alloy elements. The alloy elements are introduced to the parent metal to promote certain properties like mechanical, wear and resistance to corrosion. During friction stir welding of homogenous and heterogeneous aluminium alloys, these properties are altered. This is due to severe plastic deformation of the metals being joined together. Severe plastic deformation can result to chemical and microstructural changes. (Arora et al., 2014), (Bousquet, Poulon-Quintin, Puiggali, Devos, & Touzet, 2011), (Davoodi, Esfahani, & Sarvghad, 2016), (Chen, Li, & Hihara, n.d.).

Gharavi et al (Gharavi, Matori, Yunus, Othman, & Fadaeifard, 2015) investigated corrosion morphology and microstructure analysis of friction stir welding of AA6061-T6 Aluminium alloys. They revealed that the welding process affected the resistance to corrosion of the joint due to the degradation of intermetallic particles. They further show that by reducing the size of the grains in the weld region, the resistance to corrosion is reduced. Also, Chen et al (Chen et al., n.d.) in their investigation of mechanical properties, microstructure and corrosion of friction stir welding of 6061 Aluminium alloy, reported that corrosion is lowest in the stirred zone of the weld as a result of microstructural specimen orientation. Ralston et al (Ralston, Birbilis, & Davies, 2010) studied how grain size affects corrosion and concluded that corrosion resistance of smaller strain containing mainly large undissolved size is poor and that increase of strain leads to better resistance to corrosion. Similarly, Ralston et al (Ralston, Fabijanic, & Birbilis, 2011) in another study on high purity Aluminium alloy also concluded that corrosion tendency is high when the grain size increases and low when the size decreases. Bousquet et al (Bousquet et al., 2011) investigated the connection between hardness, corrosion susceptibilities, and microstructure, of AA2024-T3. They showed that the heat affected zone (HAZ) close to the thermomechanical

affected zone (TMAZ) has the highest susceptibilities to intergranular corrosion. This is due to the occurrence of unbroken line S^I (S) intergranular precipitates at the edges of the grain. In addition, the pitting corrosion observed was as a result of intermetallic fragmentation of the particles due to the stirring action of the tool during the welding. Davoodi et al (Davoodi et al., 2016) investigated corrosion and microstructure behaviour of FSW zone of aluminium AA5083/AA7023 dissimilar weld. Corrosion examination revealed that resistance to corrosion of weld areas lies in-between that of AA5083 and AA7023, and that AA5083 has comparatively lower volt potential than AA7023. They further added that corrosion begins at the weld boundary and the regions around intermetallic particles, especially in AA7023 side.

In a related development, the resistance to corrosion behavior of FSW of AA71080-T79 aluminium was studied by Wadeson et al. (Wadeson et al., 2006). Results obtained show that the boundary thermomechanically affected zone (TMAZ) was prone to corrosion. The report also indicates intergranular occurrence of localized corrosion. This was attributed to non-uniformity in the distribution of $MgZn_2$ precipitates in the TMAZ unlike the parent alloy that had its precipitates relatively uniform in distribution. Further influence of precipitates on corrosion behavior was revealed in the study of FSW of 2024 Al alloy by Wang et al (L. Wang, Hui, Zhou, Xu, & He, 2016). Microstructural evaluation of the alloy revealed the occurrence of two different phases of precipitates in the base alloy. Al_2CuMg and Al-Cu-Fe-Mn phase. The distribution of Mg in the first phase of the weld was not uniform with greater concentrations at the middle, which diminishes towards the edge of the particles.

Also, the corrosion susceptibilities of weldzone of a Friction Stir Welded joint of 2050 Al-Cu-Li alloy was studied by Proton et al (Proton et al., 2013). The outcome revealed that the weldzone was prone to inter and intragranular corrosion. This type of behaviour in corrosion was due to differences in microstructures noticed on a small dimension. Also, differences in corrosion characteristics of the weld zone noticed on a small scale were due to different behavior of corrosion from one end of the weld zone to another and also by a localization of the damage by corrosion attributed to the "Onion ring structure". (Ralston et al., 2011)

The relationship between microstructure and corrosion behavior might have been established from the above literature. However, a comprehensive understanding of the corrosion mechanism, grain refinement, and processing applicable to different grades of aluminium alloys is yet to be fully developed.

Effects of Additions of Alloys and Reinforcements

Effects of addition of alloys on corrosion behaviour in friction stir welding have been experimented. Recently, the corrosion behavior of Zn modified friction stir welding of Al-Mg alloys was investigated by Hou Longgang et al (Hou Longgang, Yu Jiajia, Zhang Di, Zhuang Linzhong, Zhou Li, 2017). Their results indicated that both maximum corrosion depth, and the dominating corrosion mode vary with increase in Zn content. The addition of Zn changes the corrosion from intergranular corrosion to pitting corrosion. In another research, Vijaya Kumar et al (Vijaya Kumar, Madhusudhan Reddy, & Srinivasa Rao, 2015) experimented the effect of Boron carbide (B_4C) addition on the corrosion susceptibilities of FSW of AA7075 alloy. They concluded that the B_4C nanoparticles addition significantly improved pitting corrosion of the weld. Furthermore, Kartsonakis et al, (Kartsonakis, Dragatogiannis, Koumoulos, Karantonis, & Charitidis, 2016) studied corrosion characteristics of dissimilar friction weld of (AA)6082-T6 and AA5083-H111 aluminium alloy. Multi-walled carbon nanotubes, cerium molybdate (CeMo) and titanium carbide reinforced with 2-mercaptobenzothiazole (MBT) were used as nanoadditives. The sample susceptibilities to corrosion with nanoadditives and that without nanoadditives were examined using electrochemical techniques. The outcome showed that the addition of CeMo and MBT as the FSW takes

place improved resistance to corrosion of the final metal. This was due to the accumulation of $(MoO4)^{-2}$ ions that emanate from the shell container to the outer surface of the two alloys and the development of stabilized complexes among the thiol groups of MBT and also due to the alloy of the metals stopping the entrance of chloride. In another study by Hatamleh et al (Hatamleh, Singh, & Garmestani, 2009) on corrosion susceptibilities of AA7075 Aluminium alloy during peened friction stir weld, the samples were brought under slow strain rate examination in 3.5% NaCl solutions. Observation showed no sign of stress corrosion cracking SCC or pitting corrosion on the welded sample during the slow strain rate test. However, exposure of the friction stirred welded plates to 3.5% NaCl solutions for 60 days showed pitting corrosion on the sample, but stressed corrosion cracking was not observed on any of the peened and unpenned samples. The results generally show that the rate of corrosion was small for all treated surface samples. Sizes and number of pits was larger on the unpenned surface and smaller on the shot peened surface.

Effects of Welding Parameters

Researchers have revealed that corrosion behavior of weldments could also be influenced by processing parameters like tool design, rotational and transverse speed etc. This is because, these factors influence the extent of mixtures, highest temperature attained, temperature gradient and the distribution of heat. (Arora et al., 2014), (Elatharasan & Kumar, 2014). The effects of process parameters and its influence on corrosion is reviewed in this section.

D'Urso et al (D'Urso, Giardini, Lorenzi, Cabrini, & Pastore, 2017) investigate the influence of the processing parameters on resistance to corrosion of friction stir welding of aluminium AA2024 and AA7075. The welding was carried out with varied processing parameters, like rotational speed and rate of feed. The corrosion behavior of welds was studied using local unconstrained corrosion potential evaluation to locate the anode and cathode regions of the welds. The outcome revealed that the lower hardness region has greater anodic free corrosion potential than the closest areas. The potential difference between the various regions of the welds results to galvanic corrosion of the less susceptible region. The anodic position and the region covered were determined by both the welding parameters and the alloy. In the case of AA2024, an intense pitting and crevice attack were observed while the AA7075 showed exfoliation corrosion on the rolling bands. Joining both alloys resulted in intense galvanic corrosion damage on the AA7075 in the lower hardness region. The decrease in hardness and the difference in electrochemical behaviour of the weld were caused by microstructural disruption of the alloys during the FSW. The authors concluded that the connections between process parameters and welds joint properties have led to the identification of the optimum welding conditions. Hassan et al (A. S. Hassan, Mahmoud, Mahmoud, & Khalifa, 2010) studied the corrosion morphology of dissimilar friction stir welding of A319 and A356AL alloy. Effects of welding and tool rotation speed including post-weld heat treatment (PWHT) on corrosion susceptibilities were also studied. Tool rotational speeds of 1800, 1400 and 1120 rpm with welding speeds of 112 and 80mm/min were used. The PWHT was carried out at duration of 12 hours with the temperature at 540^0C and then aged at 155 °C for a period of 6 hours. Corrosion resistance test of the welds was carried out by immersing it for 6 hours in a solution of sodium chloride (NaCl) and hydrogen peroxide (H_2O_2). The results indicate that both as welded and post weld heat treated samples exhibited higher resistance to corrosion than both base alloys. Resistance to corrosion of the weld portion was equally found to reduce when the tool rotational speed increase and/or when the welding speed reduces. In another study on effects of processing parameter on corrosion of FSW of AA2024-T345 by Jariyaboon et al (Jariyaboon et al., 2007), results obtained show that rotational speed determines the attack location in the weldment region. For low speed, corrosion attack mainly occurs in the stir zone whereas for higher speed it occurs in the heat affected zone. In

related research, Bousquet et al (Bousquet et al., 2011) results were in agreement with the above. Their result also indicates that corrosion susceptibility in the Heat Affected Zone (HAZ) was attributed to S^{I}-(S-Al_2CUMg) phase at the boundaries of the grains. Also Kang et al (Kang, Fu, Luan, Dong, & He, 2010) showed that pitting corrosion density and the extent of the attack was a bit greater in the shoulder area during FSW of AA2024-T3. They also observed that optimum welding parameters can improve resistance to corrosion of weldment. Also, Esmaily et al. (Esmaily et al., 2016) in their findings on the friction stir weld of AA6005-T6 alloy reported that the nugget zone is prone to pitting corrosion, but the range of the pitting corrosion attack in the nugget zone reduces with increase in number of friction stir passes. However, an increase in the number of friction stir passes induced pitting corrosion in the HAZ of the weld. Another outcome of research by Venkata subramanian et al (Venkatasubramanian, Mideen, & Jha, 2012)) on corrosion behavior of FSW of 2219 Aluminium alloy evaluated at different depth show that the upper surface of the welded zone has stronger corrosion resistance and it reduces with depth. Also, the stirred region was found to have better resistance to pitting corrosion than the parent metal and that the resistance to corrosion reduced with an increase in traverse speed for fixed tool rpm. Furthermore, higher tool rpm led to coarsening of the Al_2Cu precipitates, thereby increasing pitting corrosion in the nugget region. However, for friction stir welding of dissimilar alloys of Al and Cu, Esther and Andrews (Esther T Akinlabi, Andrews Anthony, 2014) reported that corrosion behavior improved as the rotational speed of the tool increased. In another related study Elatharasan & Kumar (Elatharasan & Kumar, 2014) evaluated corrosion resistance of FSW of AA7075 and found that HAZ of the weld showed the highest tendency to intergranular corrosion and that resistance to corrosion decreases with increase in the traverse speed.

It is obviously established that welding parameters influence to a considerable extent the corrosion susceptibilities of welds. More experimental findings to optimize these process parameters to achieve a reduction in corrosion rate for different friction stir welding of homogenous and heterogeneous aluminium alloys will still be of great benefits.

Corrosion in Welds and Their Parent Metals

Comparing the corrosion characteristics of base metal with their similar friction stir welded joints, de Abreu et al (de Abreu et al., 2017) studied multiple scale electrochemical structures of FSW of 7475-T651 and 2024 -T3 aluminium alloys. Their result shows higher corrosion in the stir zone of the weld compares to the two-parent metals. Galvanic coupling occurred with AA7475 acting as the anode and AA2024 as the cathode. Zn deposit reportedly occurred on the intermetallic particles of the AA2024 after a day. However, Wang (H. Wang, 2016) results on FSW of 7022 alloys showed that the corrosion in the base alloy is greater than that of the welded joints and that corrosion resistance optimum result was obtained at 400rpm and 30mm/min. This result was in agreement with Zhao et al's study on FSW of 6082 aluminium alloy corrosion performance. Also, Chen & Hihara (Chen, Li, & Hihara, n.d.) investigated FSW of 6061 Aluminium alloys and reported that FSW improved the corrosion resistance and that the heat affected zone had better corrosion resistance than other regions of the weld. This was in agreement with their separate studies on corrosion of FSW of AA5086 under the same electrochemical conditions. Contrarily Dudzik & Jurczak, (Dudzik & Jurczak, 2016), evaluation of the corrosion properties of FSW of AW7020 alloy in seawater revealed that the parent metal exhibit better corrosion in seawater condition than the friction stir welded joint which shows more susceptibilities to corrosion. Further comparison of parent metals to friction stir welded samples was also carried out by Corral et al (Corral, Trillo, Li, & Murr, 2000). They studied pitting corrosion and stress corrosion cracking of FSW of 5454 in O- and –H34 tempers. The welded joint was discovered to exhibit better resistance to pitting corrosion than the parent metal. Discontinuities defect that may be associated with

remnants boundaries of the base metal were noticed. These defects led to an increase in corrosion susceptibilities intermittently.

Corrosion in Different Electrochemical Solution

The corrosion behaviour of welded samples could be greatly influenced by the electrochemical conditions, in which it is used. Some authors have investigated corrosion of friction stir welded sample in various electrochemical solutions. Pao et al. (Pao, Gill, Feng, & Sankaran, 2001) studied crack growth of corrosion fatigue of FSW 7050 aluminium alloy in both air and 3.5% NACl solutions They reported that corrosion fatigue growth rate in air in the welded zone is a little greater than that of the base metals but in the heat affected zone, the fatigue is lower in both air and in the 3,5% NACl solutions. In related work, Zucchi (F. Zucchi, 2001) studied corrosion behavior of FSW of 5083 in 3.5% NACl and EXCO solution. The FSW showed higher resistance to corrosion in EXCO and lower pitting corrosion susceptibilities than the parent metal.

More studies could focus on the use of different electrochemical conditions depending on the area of applications of the weld.

Corrosion in Dissimilar FSW of Aluminum Alloys

Corrosion susceptibilities of FSW of dissimilar Aluminium alloys have been investigated by various researchers. Jayaraj et al (Jayaraj, Malarvizhi, & Balasubramanian, 2017) reported that interrelated microstructure could be noticed in the stir zone of FSW of dissimilar Aluminium alloys own to the mixing of the two alloys. The complex flow pattern of the stir zone gave rise to galvanic coupling, because of the differences in potential between the two metals. This makes studying corrosion in dissimilar metals imperative. LU. Donatus et al (LU.Donatusa, G.E.Thompsona, X.Zhoua, J.Wanga, A.Cassella, 2015) in another study examined corrosion behavior of dissimilar FSW of AA5083-0 and AA6082-T6 alloys. They established in their report that high welding speed increased proneness to corrosion and that the HAZ of the two alloys, the Mg_2Si particles distribution along the grain boundaries of the both alloys and the galvanic contacts of the two alloys were the cause of the weld corrosion susceptibilities. Corral et al's (Corral et al., 2000) outcome on the investigation of corrosion performance of FSW of 2024 and 2195 Aluminium alloys shows that both alloys exhibit nearly the same corrosion potentials with their FSW joint. In another corrosion investigation in dissimilar weld of aluminium alloy, Jariyaboon et al (Jariyaboon et al., 2006) established that the stirred zone of the friction stir welded AA2024 and AA7010 is prone to intergranular corrosion damage. However, Dilip et al (Dilip, Koilraj, Sundareswaran, Janaki Ram, & Koteswara Rao, 2010) in their findings on corrosion behavior of FSW of Aluminium alloys reported that the corrosion characteristics exhibited by the dissimilar friction stir welded joint of 2219 and 5083 was better than that of similar FSW of 2219 and 5083 and also better than the 2219 base materials. Furthermore, Ahmad et al (Ahmad, Ul-Hamid, & B.j, 2001) welded another dissimilar aluminum, alloys 5052 H34 and 7075-T6 and examined the corrosion behavior of the weld using potentiostat in two solutions 0.5% HCl and 0.5% NaOH. Tafel extrapolation and cyclic polarizations methods were employed to measure the specimen's resistance to pitting corrosion. The findings obtained showed that the best resistance to corrosion of welded joint was obtained in 0.5% NaOH compared to 0.5% HCl. The rate of corrosion of FSW joint was greater than base alloys in 0.5% NaOH, whereas it's lower than base alloys in 0.5% HCl. The Base metal alloys are more prone to pitting corrosion than the friction stir welded joint. The joint showed better resistance to corrosion in NaOH and HCl media. In related research, Wei & Gao (Wei, Liao, & Gao, 1998) investigated corrosion resistance of base Al-alloys 2024-T3 and 7075-T73 similar and dissimilar friction stir welded alloys in seawater (3.5% NaCl solution) at ambient

temperature using Potentiostat. The outcome of corrosion behaviour indicates that the parent alloys has higher corrosion resistance than the weld. This is due to particle content and secondary phases formed during stir welding that act as active zones to increase pits thereby promoting corrosion in seawater. Dissimilar welded Al2024-T3/Al7075-T73 showed higher susceptibilities to corrosion than the galvanic coupling of the same alloys. The potential and corrosion current density of dissimilar welded Al2024-T3/Al7075-T73 were given as -793.7 mV and 5.32 $\mu A.cm^{-2}$ respectively, whereas, galvanic coupling had potential equal to -653 mV with a current density of 1.0025 $\mu A.cm^{-2}$. It was also shown that the rate of corrosion of dissimilar weld was lower than that of similar welds of Al2024-T3 and Al7075-T73.

The literature survey in this section indicates that corrosion behavior of all dissimilar friction stir welded aluminium alloys is not homogenous. All the aluminium series have varying properties in terms of corrosion resistance and the type of corrosion attack suffered by the materials. Processing parameters and other factors equally play a role in determining corrosion morphology in friction stir weld of heterogenous aluminium alloys. Proper correlation of corrosion susceptibilities with properties exhibited in dissimilar aluminium alloys welded joints could be explored further.

Effects of Post-Weld Heat Treatment (PWHT)

Reports from various researchers have shown that post weld heat treatment has effects on corrosion characteristics. Vijaya Kumar et al. (Vijaya Kumar et al., 2015) performed retrogression and reaging (RRA) post-weld heat treatment on friction stir welded (FSWed) joint of AA7075 to determine the corrosion behavior. Their findings show appreciable improvement in pitting corrosion resistance. Stress corrosion cracking (SCC) is enhanced but with little loss in hardness. Post weld artificial aging (PWAA) method has been applied to some alloys to reduce stress corrosion cracking. Pao et al (Pao, P.S., Gill, S.J., Feng, C.R., and Sankaran, 2001) have shown the restoration of resistance to stress corrosion cracking in 7050-T7451 through PWAA for a 24hour at 121^0c after testing in a 3.5% NaCl solution. Sankaran et al (Sankaran, K.K., Smith, H.L., and Jata, 2002) in another study evaluated the corrosion susceptibilities of some Aluminium alloys after PWAA treatment. Their result showed that corrosion behavior of the welded joint is comparable to that of the parent metal. Similarly, Dunlavy and Jata (Dunlavy, M., and Jata, 2003) evaluated the corrosion fatigue behavior of the combination of the same alloy after PWAA. Their result showed that the fatigue strength of the welds decreased by half. Widener et al (Widener, Burford, Kumar, Talia, & Tweedy, 2007) also attempted to improve the corrosion performance of 7075 Aluminium alloy through a various combination of PWAA and starting temper. The 7075-T73 and 7075-T6 were passed through PWAA. They concluded that welding in T73 followed by PWAA performs better in terms of corrosion resistance than welding in T6 temper and aging to T73. They equally added that PWAA for about 4hours at 325^0F enhanced resistance to corrosion.

Research has shown that PWAA has the potential of restoring SCC. However, it has been reported that in some cases, it reduces resistance to exfoliation. RRA has equally been experimented but not widely.(Widener et al., 2007), (Leonard, 2000). More investigations on PWHT using RRA and PWAA to restore corrosion resistance still beckon on researchers.

WEAR

The response of friction stirred welded joint of Aluminium alloys to wear processes is important for the industrial application. Wear characteristics of friction stir welded joints has been reported by some researchers. The following sections examine the literature in this regard.

Wear Testing Method

Tribometer is an instrument that measures wear. The machine, basically controls mechanical loading, measure frictional force, normal force and evaluation of coefficient of friction (COF) with time and rate at which materials are removed (Kuiry, 2012).

Most of the main friction and wear tests were done via a ball-on-flat configuration in reciprocating sliding and with a pin on disk configuration in a one-directional sliding. Pin on disk wear testing is a technique of analyzing force of friction, frictional coefficient and rate at which wear takes place between two metals. (Syed Khaja N, Md Tousef a, Purna, B. C, Narendra Mohan, Vidhu Kampurath, 2016), (Ponthiaux et al., 2012), (Dinaharan & Murugan, 2011)

The effects of sliding velocities and contact load of the pin-on-disk machine on the rate of wear have been investigated. Wang and Zhang (A. Wang & Rack, 1991), (Zhang & Alpas, 1997), have reported that wear mechanism may change suddenly at particular sliding velocities and contact loads resulting to sudden increase on the rate of wear. Investigations by Glaeser and Ruff showed that Pin-on-disk was the most used wear test method followed by the pin-on-flat method. (Ludema & Bayer, 2012), (A. Wang & Rack, 1991).

Wear in Similar and Dissimilar Friction Stir Welding

Analysis of wear behaviour in similar and dissimilar friction stir welding available in literature have been reviewed below.

Seyed et al (Syed Khaja N, Md Tousef a, Purna, B. C, Narendra Mohan, Vidhu Kampurath, 2016) investigated wear behaviour in similar and dissimilar FSW of AA6061 and AA6082. The wear analysis results revealed that similar welds of AA6061 sample gave better resistance to wear in the welded zone than the other welds. However, dissimilar AA6061-AA6082 weld specimen gave better wear performance in the non-welded zone. Another study on wear behaviour of the same alloys above was carried out by Khaja et al (Khaja Naimuddin, Md, Vidhu, Asim Mohamad, & Ali, 2016). They studied the wear resistance of FSW joint of similar AA6061 and similar AA6082. The wear results obtained from each of the above were compared to that of dissimilar friction stir welded (FSWed) joint of the two alloys. They concluded that FSW of similar AA6061 materials is the most resistance to wear in comparison to similar FSW of AA6082 and dissimilar FSW of both metals. These results show agreement with Seyed et al (Syed Khaja N, Md Tousef a, Purna, B. C, Narendra Mohan, Vidhu Kampurath, 2016).

In related work, Dubey et al (Dubey, Kumar, & Yadav, 2017) investigated the wear characteristics and hardness for FSWed and unwelded portion of cast Al (4-10%) Cu alloy. They discovered that the highest hardness value was obtained at the middle of the nugget region followed by a systematic reduction across the (TMAZ) and the (HAZ). This was correlated with friction stir behaviour.

Effects of Additions of Reinforcements and Processing Parameter on Wear

Wear investigation on FSWded aluminium alloy with the addition of materials as reinforcement has also been carried out. Kalaiselvan and Murugan (Kalaiselvan & Murugan, 2013) studied wear behaviour of Aluminium 6061-B_4C composite. They reported that the occurrence of fine grain microstructure and B_4C particulates in the welded region improve the wear behaviour. In related research, Farahmand and Parvin (Farahmand Nikoo, Parvin, & Bahrami, 2017) investigated wear characteristics in aluminium AA6061-T6 reinforced with nano-particles Al_2O_3 during friction stir

welding and found atremendous improvement in wear resistance.

The effects of processing parameters on wear was reported by Dinaharan & Murugan (Dinaharan & Murugan, 2011). They investigated the influence of FSW parameters on sliding wear properties of AA6061/0-10wt and reported that the rate of wear reduces as tool rotational speed goes higher, but further rise in tool rotational speed could result to increase in rate of wear. A similar study was also performed by Adel et al (A. M. Hassan, Almomani, Qasim, & Ghaithan, 2012) however, their welding was carried out with SiC and graphite reinforced aluminium matrix composite. The wear behavour in relation to the welding parameters investigated revealed an increase in wear resistance of the weld at higher traverse speed and lower rotational speed. Pin profile on the wear characteristics was also studied. The results show that the square pin profile performs better than hexagonal and orthogonal pins investigated. In a related study, Mirjavadi et al (Mirjavadi et al., 2017) welded 5083 aluminium alloy reinforced with TiO_2 using FSW. The optimized parameter was processed from 1 to 4 passes. The wear behaviour investigated indicates a significant improvement in wear resistance for samples welded through four passes.

Temperature influence on the rate of wear for Aluminium silicon alloys has been investigated by Rajaram et al (Rajaram, Kumaran, & Rao, 2010). Their findings showed that the rate of wear decreases when the temperature decreases.

The available literature reviewed above on wear behaviour in FSW shows that welding parameters and additions of other elements as reinforcements to the aluminium matrix considerably affect the wear characteristics. In most cases, improvement is noticed in wear resistance of the reinforced aluminium alloy. Proper choice of operating welding parameters could also enhance wear resistance. More research efforts on wear characteristics of different aluminium composites and grades similarly and dissimilarly welded through FSW under different welding parameters will further broaden the knowledge-based on wear mechanism in FSWded aluminium alloys.

CONCLUSIONS

An overview of wear and corrosion mechanism in friction stir welding of aluminium alloy has been presented. The review highlighted various forms of corrosion mechanism and wear in friction stir welding. The review shows that the weld parameter is a key factor that influences corrosion and wears. Proper control of the weld parameters could help achieve the desired microstructural evolution for proper bonding and high resistance to corrosion and wears. Although the correlation between wear, corrosion, microstructure, mechanical properties, and welding parameters have been established in this reviewed. However, comprehensive knowledge and more understanding of the mechanism involved may still need to be explored. A considerable amount of works has been done separately on wear and corrosion of welded samples of various aluminium alloys, however, the combine effects of wear and corrosion on friction stir welding of aluminium alloys is yet to be fully reported. Findings from a separate experimental study of wear and corrosion may not be sufficient to evaluate the durability of weld, since most corrosion resistance elements are not wear resistance and vice versa. There is complexity in the results of combining wear and corrosion. Information from tribological (wear) behaviour without a corrosive medium and that of the electrochemical behaviour without wear is not adequate enough to fully predict the performance of friction stir welds. Friction and wear affect the susceptibilities of material to corrosion, and conversely corrosion influences the conditions of frictional wear. There is a synergy between wear and corrosion. Therefore; there is a need for further investigation on the combined effect of wear and corrosion in friction stir welding of aluminum alloys. More understanding of the mechanism of interactions of mechanical and electrochemical in friction stir welds will assist in predicting the performance and lifetime of welds.

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